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Present and Future X-ray Tomographic Microscopy at TOMCAT

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Isenegger, A ; Stampanoni, M

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Present and Future X-ray Tomographic Microscopy at TOMCAT

F. Marone^a, R. Mokso^a, P. Modregger^{a,b}, J. Fife^{a,c}, B. Pinzer^{a,b}, T. Thüning^{a,b},
K. Mader^{a,b}, G. Mikuljan^a, A. Isenegger^a, and M. Stampanoni^{a,b}

^aSwiss Light Source, Paul Scherrer Institut, Villigen, Switzerland

^bInstitute for Biomedical Engineering, University and ETH Zurich, Zurich, Switzerland

^cComputational Materials Laboratory, EPFL, Lausanne, Switzerland

Abstract. During its first four years of life, the TOMCAT beamline [1] at the Swiss Light Source has established itself as a state-of-the art hard x-ray tomographic microscopy endstation for experiments on a large variety of samples, ranging from the fields of biology to materials science. It routinely performs absorption as well as phase-contrast imaging with an isotropic voxel size ranging from 0.360 up to 14.8 microns. Phase contrast is obtained either with simple edge-enhancement, a modified transport of intensity approach [2] or grating interferometry [3]. Typical acquisition times are on the order of a few minutes, depending on energy and resolution. A recently implemented automatic sample exchanger is now available for high-throughput studies [4]. In addition to further developments in phase-contrast imaging, current scientific activities at the beamline focus on pushing spatial and temporal resolution by a few orders of magnitude, aiming at nano- [5] and “real-time” [6] tomography.

Keywords: X-ray imaging, synchrotron CT, phase-contrast imaging, transport of intensity, grating interferometry, nanotomography, ultrafast tomography

PACS: 87.59.-e, 68.37.Yz, 87.64.mh, 07.85.Fv, 07.05.Pj

INTRODUCTION

In 2006, the beamline for TOmographic Microscopy and Coherent rAdiology experimenTs (TOMCAT) [1] started regular user operation. Since its “birth,” the beamline has continuously evolved until it has established itself as a state-of-the art hard x-ray tomographic microscopy endstation for experiments on a large variety of samples. This evolution has touched different aspects. From the scientific side, over time several tomographic techniques have been added to the palette routinely offered to the users, with the goal of performing always new challenging experiments. On a more technical side, attention has been devoted to the user friendliness of the beamline operation and data postprocessing. Important efforts have also been dedicated to the efficient handling of the ever-growing amount of data produced, and an optimized pipeline for data acquisition and postprocessing has been put in place. Although the beamline has reached a sort of “maturity,” evolution is still ongoing. Current scientific activities at the beamline focus on pushing spatial and temporal resolution by a few orders of magnitude. We discuss here the different novel aspects, which contribute to the high attractiveness of TOMCAT.

BEAMLINE OVERVIEW

The source for the TOMCAT beamline is a 2.9-T bending magnet with a critical energy of 11.1 keV, which provides sufficient photon flux between 8 and 45 keV. The small source size ($\Sigma_x=53$ m, $\Sigma_y=16$ μ m), coupled with high quality and sparseness of the optical components, guarantees a highly transversally coherent beam ($l_{\text{hor}}=44$ μ m, $l_{\text{vert}}=156$ μ m at 1 Å and 25 m from the source, specified as σ) even for a rather short beamline as TOMCAT. In addition to operation with white/pink beam, a fixed-exit double-crystal multilayer monochromator enables experiments with monochromatic light (2-3% bandwidth).

The TOMCAT endstation (Fig. 1) is very versatile, and its set of different microscopes and cameras allows for investigations ranging a few orders in magnitude in spatial and temporal resolution. The slip ring recently integrated in the preexisting air-bearing rotation stage enables continuous sample rotation, a feature required for “real-time” tomographic investigations. Furthermore, the generous space around the sample stage is important for *in situ* experiments, for instance with furnaces, cryo-chambers, or compression devices. A recently implemented sample exchanger guarantees automatic measurements of up to 60 samples and multiple regions of interest per sample, resulting in several hours of unattended operation [4]. In addition, a user-friendly scripting approach enables repeated measurements of a defined sequence of samples.

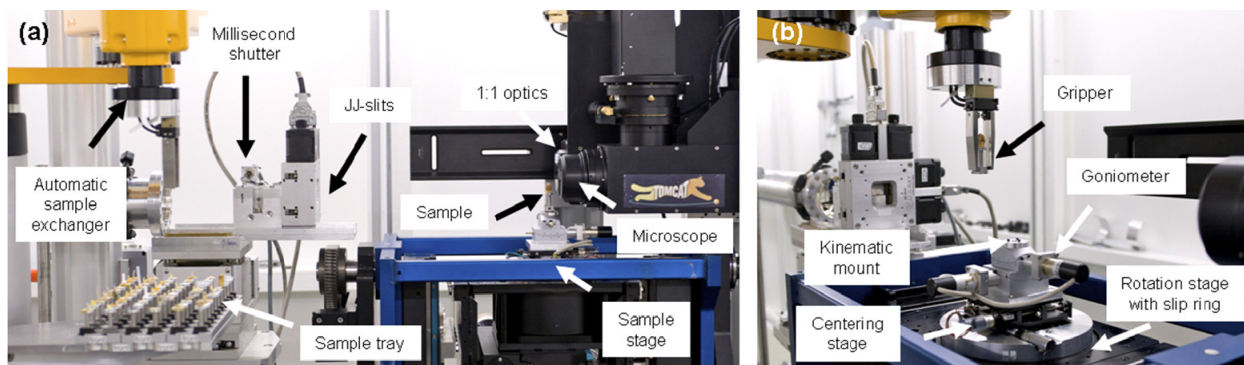


FIGURE 1. Beamline overview – (a) endstation, (b) automatic sample exchanger.

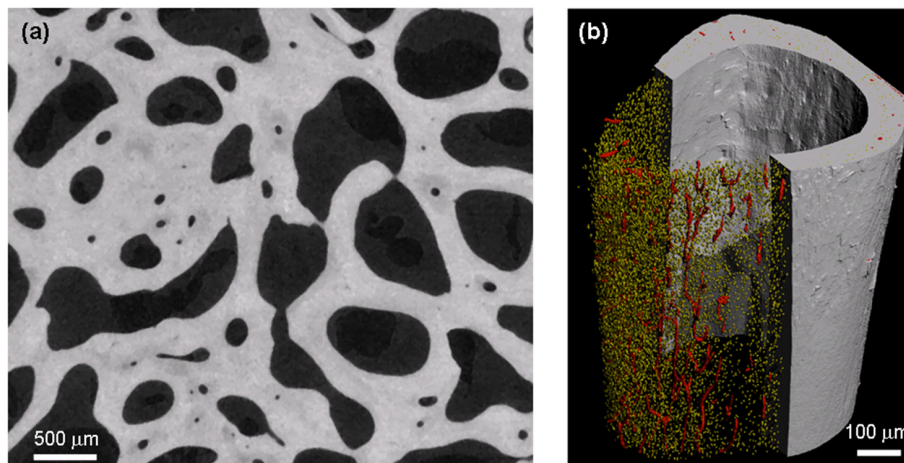


FIGURE 2. Absorption tomographic microscopy – (a) Axial slice through a bovine trabecular bone biopsy: bone with different mineralization levels are clearly visible (Sample courtesy: P. Schneider, ETH Zurich). (b) 3D rendering of the cortical region of a mouse femur. The segmented bone is shown in grey on the right, osteocyte lacunae (yellow) and the canal network (red) are highlighted on the left.

In addition to standard absorption investigations (Fig. 2) routinely reaching 1-micron resolution (Fig. 3), at the TOMCAT beamline the coherence of the beam also permits phase contrast experiments (Fig. 4). In particular besides simple edge-enhancement, two different techniques are routinely available to the user community, covering a wide range of resolutions and sensitivities. Differential phase contrast (DPC) tomography [3, 7] provides very high sensitivity and is therefore particularly suited for the study of soft tissues in native state, when moderate resolution (10 microns) is sufficient and a large field of view is required. An in-house-developed aquarium enables data acquisition with the sample in a liquid environment [7], important both for sample preservation and for reducing phase-wrapping artifacts. For higher-resolution (few microns) investigations, a phase-contrast technique based on the transport of intensity equation [2] is better suited. However, because this method is sensitive to the second

derivative of the phase signal, its sensitivity is smaller compared to the DPC approach, which instead detects the phase gradient.

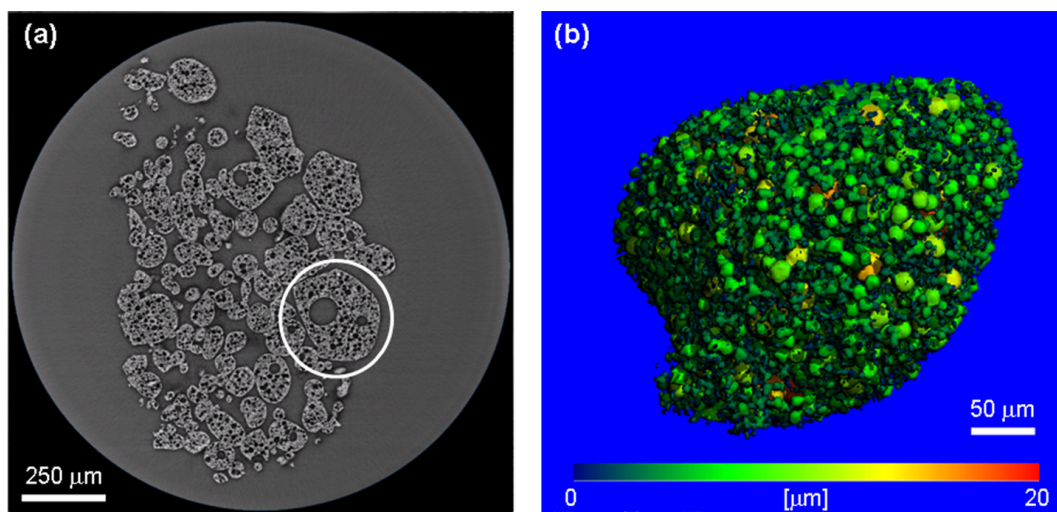


FIGURE 3. Quantitative morphometric analysis – (a) Reconstructed slice through a dried granule composed of several particles. (b) Evaluation of the porosity structure (color-coded pore size) within the particle encircled in (a).

The acquisition and postprocessing pipeline for the different tomographic experiments has been strongly optimized to enable fast data recording and reconstruction [8], in a user-friendly manner. High-quality datasets (12 GB) are typically acquired in about 10 minutes. A reconstructed high-resolution volume ($2048 \times 2048 \times 2048$, 1500 projections) is available 2 minutes after the end of a scan, while a selection of reconstructed slices can be visualized through a web interface immediately at the end of a scan. This interface also allows the fine-tuning of the reconstruction parameters and the submission per mouse click of the full reconstruction job to our dedicated cluster. This strong postprocessing optimization enables real-time quality control as well as efficient data reconstruction in parallel with data acquisition, providing the users with full reconstructed data volumes at the end of their beam time.

Quantitative morphometric analysis capabilities are also available on site (Fig. 3).

ONGOING DEVELOPMENTS

Current efforts are devoted to the development and implementation of two different endstations, aimed at improving spatial and temporal resolution by a few orders of magnitude. In terms of spatial resolution, the goal is a 3D isotropic resolution on the order of 100 nm. For this purpose, full-field geometry with magnification in the x-ray regime is mandatory. Using in-house-developed x-ray optics, a full-field hard x-ray (10 keV) microscope has been built, with both absorption and phase-contrast capabilities [5]. The used beam shaper [9] provides a square top flat illumination (50 microns) at the sample position. Different Fresnel zone plates (FZP) are used for the magnification in the x-ray regime. Zernike phase contrast is achieved by manipulating the wave field in the back focal plane of the objective FZP using a phase dot array. This new instrument, which demonstrated a 3D isotropic resolution of 144 nm, is particularly suited for imaging biological samples in their semi-native state. On one hand, because of the high energy of the beam and therefore relatively small dose deposition, no particular sample environment (e.g., cryo cooling) is needed to prevent radiation damage. On the other hand, thanks to the high sensitivity of the Zernike phase-contrast approach, intracellular structures are clearly visible without the need of a contrast agent.

The high flux of third-generation synchrotron sources coupled with new detector technology enables new time-resolved tomographic experiments, for instance the investigation of foaming processes, nucleation and growth of bubbles in magmas, or biological processes (blood flow, breathing) in living animals. The goal is to offer at TOMCAT an endstation for ultrafast (1 Hz) tomography, both with white and monochromatic beam in absorption and phase contrast. One of the main components of such an endstation is a sensitive CMOS detector, which, when coupled with efficient microscope optics and a fast rotation stage, enables the acquisition of full tomographic

datasets in less than 1 s as demonstrated during recent pilot experiments [6]. One of the main current challenges is the extremely high (> 8 GB/s) data rate produced. Innovative solutions for efficiently transferring the acquired data from the camera RAM to the central storage as well as for postprocessing and visualizing it are currently under investigation.

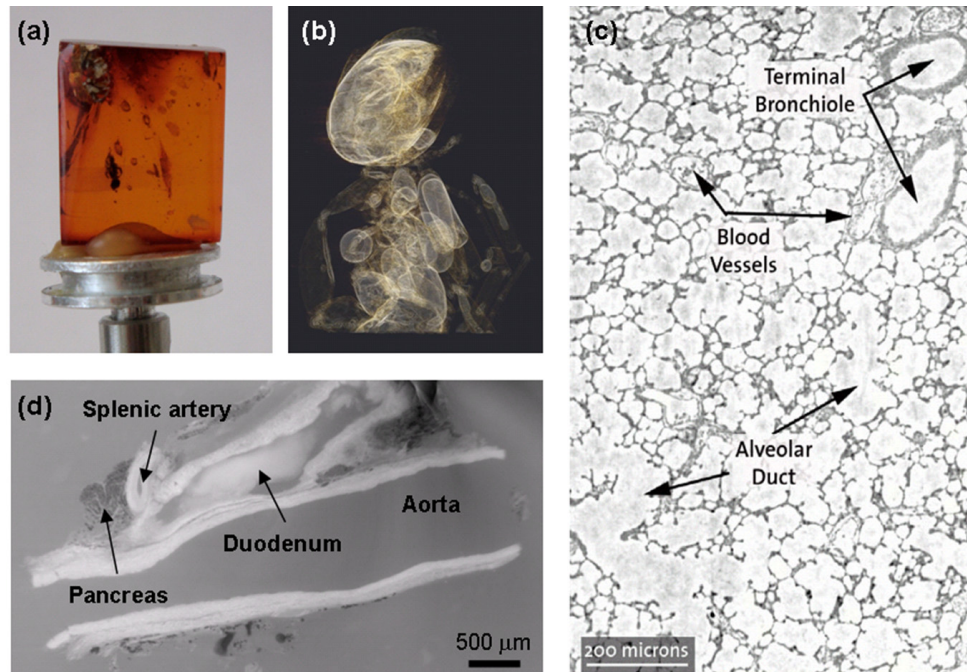


FIGURE 4. Phase-contrast tomographic microscopy – (a) 35-40 million year old insect preserved in amber (Sample courtesy: E. Friis, Swedish Museum of Natural History, Stockholm). (b) 3D rendering of the insect trapped in amber in (a). In this case, simple edge-enhancement has been exploited. (c) Slice through the phase contrast reconstruction (measured with the modified transport of intensity approach [2] of an unstained rat lung biopsy (paraffin embedded) showing the major expected anatomical features (after [10]). (d) Slice through the phase-contrast reconstruction (measured with the DPC approach [7]) of a segment of a rodent aorta (fixed in formalin) (Sample courtesy: A. Pasch, Inselspital, Bern).

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